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ELECTRIC PROPULSION

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To be competitive with chemical rocket and nuclear rocket upper stages, the electric propulsion system must be of sufficiently low weight to allow adequate payload capacity for a given mission time. Required values of performance parameters are illustrated in table I for a range of missions of interest. Electric powerplants presently available for space flight (e.g., solar cells) have specific weights well over 100 lb/kw, a value that is suitable only for missions such as satellite control. However, future electric power generation systems have promise of lower specific weight. For example, the SNAP-50 nuclear turboelectric powerplant, now in the early stages of development, is hoped to have a specific weight of 15 to 30 lb/kws (turbine shaft power) in the 300- to 1000-kw power range.

ELECTRIC SPACECRAFT PROPULSION SYSTEMS

Complete electric propulsion systems are made up of a number of subsystems or components each of which influences, by its performance and mass, the effective specific weight of the whole system. For example, a nuclear turboelectric powerplant coupled with an electrostatic thrustor might have the following masses and efficiencies:

[redacted]

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	Mass, kg/kw	Efficiency, percent
Nuclear turboelectric powerplant	10	----
Alternator	.45	92
Controls	.32	96
Transformer	.36	97
Rectifier	.23	98
Switchgear	.05	99.8
Thrustor	1.13	80
Tankage and feed system	Negligible	----

The generator and the power conditioning specific masses are for advanced technology designs with operating temperatures of 700° F. With these component efficiencies, the overall efficiency of conversion of turbine shaft power to effective jet power would be only 67 percent. In addition, the inefficiency of each component increases the required mass of the components preceding it. The resulting specific mass of the propulsion system would be 18 kg/kwj based on effective jet power.

In addition to component losses and masses, other factors contribute to reductions in spacecraft payload capacity. Two of these are (1) nonoptimum ratios of effective jet power to gross spacecraft starting mass, and (2) nonoptimum thrust programs. The first of these cannot be avoided in every mission, since boosters and electric propulsion systems will be made in fixed sizes. The second loss can be serious if (as is now the case) thrustors can operate efficiently only in a narrow range of specific impulse.

The above considerations indicate that direct coupling of electric thrustor and powerplant, high thrustor efficiency, high density propellant, and variable or multistep specific impulse operation would all do much toward improving anticipated system performance.

The present performances and operating characteristics of most thrustors now being investigated for possible propulsion applications are compared in figure 1 and table II. These comparisons will be discussed in terms of the usual three categories of electric thrustors, namely electrothermal, electromagnetic, and electrostatic.

ELECTROTHERMAL THRUSTORS

The principle of operation of electrothermal thrustors is electrical heating of propellant gas and thermodynamic expansion through a nozzle to produce thrust. These are two types of electrothermal thrustors, the arc jet and the resistojet. Although very high gas temperatures can be obtained in the electric arc, dissociation and ionization losses limit exhaust velocity if high thrustor efficiency is required. Because of nozzle cooling requirements, hydrogen appears superior to other propellants in terms of theoretical efficiency in the range of specific impulse up to 1000 seconds. Because of tankage penalties, other propellants such as lithium might be superior for a specific impulse above 1000 seconds. For example, lithium has a theoretical thrustor efficiency of about 60 percent at 1800 seconds.

In the resistojet, metal surfaces are maintained at high temperature by electric heating. Propellant gas is heated by forced convection over the heater surfaces. Specific impulse is limited by materials properties to a value of about 1100 seconds with hydrogen.

Although experimental runs of resistojets have lasted only a few hours, it appears that long life can readily be attained. Both the resistojet and the arc jet have simple electrical circuits, and the electric generator probably can be designed to produce the voltage required by the thrustor, thereby eliminating some of the power conditioning components. It is expected, however, that electrothermal thrustors will be limited to use in those few missions where very low specific impulses are required.

ELECTROMAGNETIC THRUSTORS

In general, electromagnetic thrustors operate on the principle that an electric current passing through a plasma in the presence of a magnetic field can produce an accelerating body force on the plasma. Production of a plasma by ionization requires electric power that is not converted into thrust. In addition, the propellant gas atoms that are not ionized must be accelerated by momentum interchange with the ionized atoms that have been imparted motion by the electromagnetic field. This momentum interchange is not continuous or instantaneous, so the ion is accelerated to a speed higher than that of the bulk plasma before it collides with an atom. Because of this mismatch of kinetic energy and momentum, electric power is lost in the acceleration process. If the gas pressure is lowered so the ions do not collide with the neutral atoms, then the accelerator loss becomes one of propellant rather than electric power, since a fraction of the propellant leaves the thrustor exhaust at thermal speeds.

To avoid power loss due to "ion slip" or propellant loss at low plasma density, it would seem that the propellant gas need only be fully ionized before acceleration. However, electrons recombine with ions in a plasma so that energy must be continually supplied to maintain a given degree of ionization. For complete ionization a very large power is consumed in ionizing the gas. If the plasma were at a low enough density, the power required for complete ionization might be reduced, but then the exhaust jet power density would be decreased. Since high exhaust jet power density is a possible advantage possessed by electromagnetic thrustors, lower plasma density is not attractive.

Plasma containment is another problem in electromagnetic thrustors that have a reasonably high plasma density. Ions or electrons that strike the accelerator walls will lose their kinetic energy and will recombine. Both of these factors result in power loss and may erode the walls seriously in the long operating times required in electric propulsion missions.

Operating characteristics of most of the plasma thrustor design concepts currently being studied are shown in figure 1 and table II. These values are for research models and do not represent proven thrustor performances as yet.

The repetitive-pinch and the coaxial-rail concepts both operate with a pulsed discharge and acceleration process. For low values of capacitor and thrustor specific mass, both of these devices must have a pulse rate of hundreds per seconds; and for high thrustor efficiency, capacitor ringing after each discharge must be avoided. It is hoped that newly developed capacitors, having low inductance and adequate cooling at high repitition rates, together with improved accelerator design, will increase performance of both of these thrustor types.

In the magnetic-expansion thrustor concept, plasma acceleration is accomplished directly in the electric discharge between cathode and anode. In the discharge, electrons are preferentially heated and expand out through a diverging magnetic field. The resulting electric field accelerates the ions. Some increase in efficiency is expected with improved magnetic-field configurations, but the efficiency probably will not exceed that of the Kaufman thrustor extrapolated to low specific impulse. Durability problems might be less severe than in the Kaufman thrustor, and the simplicity of the magnetic-expansion thrustor makes it appear of interest for station-keeping and attitude-control missions.

In the traveling-wave thrustor concept, magnetic waves are created by alternating current (between audio and radio frequency) impressed on magnetic field coils. The waves carry plasma along a tube to the exhaust. Efficiencies as high as 10 percent have been measured with argon and 25 percent with xenon propellant at a specific impulse of 4000 seconds. These efficiencies do not include power losses incurred in transferring electric power from the power supply to the plasma. The fraction of total electric power that has been coupled into the plasma has been only 20 to 50 percent so far, but this coupling probably can be substantially increased in the future by the use of thin pancake coils to reduce the r.f. skin-current losses.

In the Hall-current thrustor concept, an applied axial electric field accelerates plasma ions. Electrons travel in azimuthal paths because of the axial electric field and an applied radial magnetic field. With appropriate magnetic and electric field strengths, the electron drift in the upstream direction is slow enough to provide neutralization of the ion space charge without large power consumption. This thrustor concept is still in the preliminary research stage, so performance characteristics have not been determined as yet.

The hybrid-arc thrustor concept is a recent development by the Giannini Scientific Corporation and is also being investigated in other laboratories. The hybrid-arc concept involves the use of low mass flow of propellant and high current in an arc-jet configuration. Acceleration of the plasma is accomplished by a combination of arc heating, magnetic expansion, and Hall-current mechanisms in various proportions depending on the particular design.

ELECTROSTATIC THRUSTORS

For the range of specific impulse of interest for most electric propulsion missions, the electrostatic thrustor is the nearest to an acceptable performance status. In electrostatic thrustors, ions are accelerated by electric fields with essentially no power loss. Power loss and/or propellant loss occur in the ionization process. The primary power for these thrustors must be high-voltage d.c. with a fairly small ripple (e.g., 5%), so power conditioning is an important component in the electrostatic propulsion system.

The central problem in electrostatic thrustors is presently that of erosion of electrodes by secondary ions formed from charge exchange between primary ions and neutral propellant atoms in the accelerator. This problem is especially severe for the contact-ionization thrustors because high efficiency requires high ion current density, which in turn seriously increases charge-exchange ion erosion and reduces thrustor lifetime. In contact-ionization thrustors, cesium propellant atoms are ionized as they flow through and leave the porous tungsten ionizer. Although the cesium atoms are nearly all ionized in this way, the small percentage of neutral cesium atoms that leave the ionizer are enough to cause considerable electrode erosion. Solution of this problem depends critically on the development of porous tungsten ionizers having submicron pore size, high pore density (per unit surface area), and negligible sintering rate at operating temperatures of about 1600° K. Recent progress indicates that these requirements may be achievable, but to date, adequate durability of contact-ionization thrustors at high efficiency has not been established.

The Kaufman electron-bombardment thrustor is at present the only electric thrustor with adequate performance for interplanetary space missions. Propellant is ionized by electron-bombardment in an ion source that has an axial magnetic field of about 40 gauss. Electrons emitted from the cathode are attracted toward a concentric cylindrical anode by a radial electric electric field but are restrained to cycloidal paths until collision with propellant atoms occurs. Ions are extracted from the resulting plasma and are accelerated by an external electric field. The primary losses in this thrustor are the discharge power and the cathode heating power in the ion source. Although charge-exchange ion erosion of the accelerator electrodes is a problem, the efficiencies shown in figure 1 are commensurate with a 10,000-hr durability of the electrodes.

In the mercury-propellant version of the Kaufman thrustor, two cathode designs have promise of adequate durability. Oxide-coated cathodes have been operated for 3000 hrs under realistic ion-source conditions, and it is expected that this durability can be improved to 10,000 hrs. Mercury-pool cathodes are presently under development at the Hughes Research Laboratories, and it appears that adequate durability will be attained. For the cesium-propellant version of the Kaufman thrustor, the auto-cathode developed by Electro-Optical Systems, Inc. is also expected to have adequate durability.

Four auxiliary power circuits are required for the Kaufman thrustor (cathode, discharge, accelerator electrode, and neutralizer) in addition to the high-voltage d.c. primary power circuit. These requirements incur power-conditioning losses as described previously and also introduce systems problems such as protection against electric breakdowns in the thrustor.

Although the spacecraft payload would be substantially less than the theoretical maximum due to thrustor imperfections, the Kaufman thrustor has been developed to a point where it could be incorporated into an electric spacecraft propulsion system.

Electrostatic thrustors using heavy-particle propellants may have promise of filling in the efficiency gap between electrothermal thrustors and the Kaufman thrustor (see fig. 1). In principle, high efficiency would be possible with propellant ions having greater than 1000 amu/ electronic charge even if ionization power losses were greater than those in the Kaufman thrustor. Heavy-molecule propellants have been investigated, but severe molecular fragmentation occurs presumably because of the electron-bombardment process. Colloidal particles have been generated and charged with a mass of 100,000 amu/electronic charge, and thrust has been demonstrated with laboratory devices. At present, special instrumentation is being developed to provide means for accurate evaluation of colloid thrustor performance. In order to reduce the primary power voltage level to a few hundred thousand volts, research is also underway to reduce the mass per charge of colloidal propellants. Research of this kind offers hope that the efficiency gap can be closed so that propulsion systems with multiple-step specific impulse could be used to reduce the payload loss due to nonoptimum thrust programming.

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TABLE I. - PERFORMANCE REQUIREMENTS FOR ELECTRIC SPACECRAFT TO BE COMPETITIVE

WITH CHEMICAL AND NUCLEAR ROCKETS

Mission	Chemical booster	Jet power, kwj	Constant specific impulse, sec	Thrusting time, days	Maximum specific mass of propulsion system, kg/kwj
Control of synchronous satellites	Centaur	1	7,000	50 to 2000	100
Lunar ferry (5 round trips)	Saturn 1B	400	5,000	400	10
Mars orbiter (300 nm Mars orbit)	Saturn 1B	400	5,000	180	15
Pluto orbiter (150-nm Pluto orbit)	Saturn 1B	400	14,000	2000	10
Manned Mars round trip	Saturn V	4000	9,000	350	10

TABLE II. - CHARACTERISTICS OF EXISTING ELECTRIC THRUSTORS

Thrustors	Propellant	Typical design specific impulse, sec	Thrustor efficiency	Anticipated design durability, days	Module effective jet power, kwj	Thrustor specific mass, kg/kwj	Nominal primary power voltage, v	Number of auxiliary power supplies
Resistojet	H_2	800	0.65	1000	20	0.13	-------	0
Arc jet	H_2	1,500	0.44	[a]30	132	0.03	200 d.c.	0
	NH_3	1,000	0.40	[a]30	12	0.03	150 d.c.	0
Magnetic expansion	Ar	2,000	0.20	400	0.02	----	50 d.c.	1
Traveling wave	Xe	4,000	----	----	------	----	(150 kc r.f.)	2
Coaxial rail	Ar	5,000	0.30	----	------	----	-------	0
Repetitive pinch	Ar	5,000	0.30	----	------	----	-------	0
Hybrid arc	H_2	10,000	0.50	----	120	0.05	100 d.c.	1
Contact ionization	Cs	10,000	0.74	400	------	----	6,500 d.c.	3
Kaufman	Hg	9,000	0.88	400	22	0.5	10,000 d.c,	4
	Cs	10,000	0.80	400	------	----	8,000 d.c,	4

[a]Actual demonstration runs (design durability may be greater).

E-2660

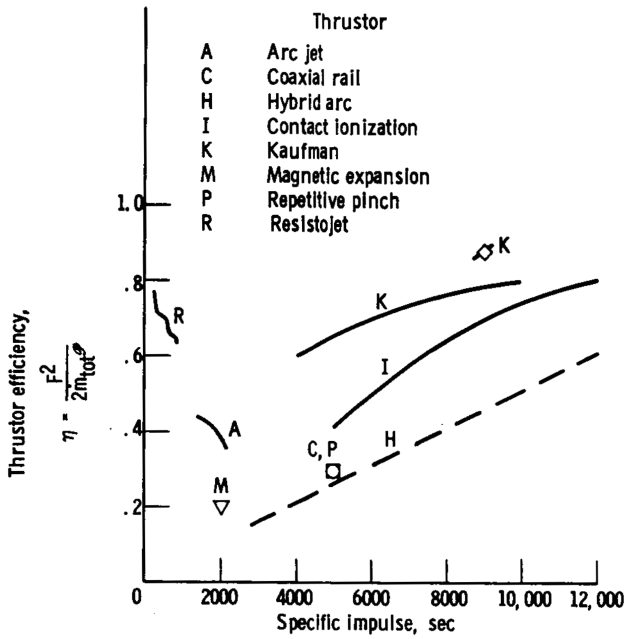

Figure 1. - Electric thrustor efficiencies where F is thrust, $\dot{m}_{tot}$ is total mass flow rate of propellant, and $\mathscr{P}$ is total electric power input to the thrustor.